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Late Quaternary climates of Western Australia: evidence and mechanisms

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Abstract

An attempt is made to provide an outline of the climatic history of Western Australia over a period of the order of 80 000 years, for which some information is available even if sketchy and poorly dated. The late Quaternary was characterised by marked changes in climate, with possibly quite contrasting conditions occurring simultaneously in different parts of Western Australia; the dominant feature, however, was an intensification of aridity. A massive extension of the arid zone coincided with the last global glacial maximum. A consideration of the mechanisms responsible for this event suggests that this was a recurrent theme of the Pleistocene, an interpretation which appears to be supported by the available stratigraphic evidence.

Introduction

In recent years substantial progress has been made in establishing the Quaternary palaeoclimatic history of Australia (see Bowler *et al.* 1976). Unfortunately our knowledge of the Western Australian palaeoclimatic record is sparse when compared to its eastern counterpart. While there exists a large volume of literature which contains reference to Quaternary climatic changes that may have taken place in Western Australia, much of this work suffers from the absence of a satisfactorily-dated framework within which the scattered observations can be placed, and is marred by the tendency of some authors to invoke climatic change as a ready explanation of features which in many cases may be adequately explained by other factors. More recent work, which has been facilitated by both the documented climatic changes that are known to have taken place in other parts of Australia, and the initial results of the Climap project, has shown an explicit concern with the nature and sequence of Quaternary climatic events in Western Australia. It is largely from this work that a framework for understanding the Quaternary climatic and environmental history of Western Australia has begun to emerge.

The aim of this paper is (1) to survey the major evidence that has been advanced by various authors to reflect the Quaternary climatic variations that may have taken place in Western Australia, and from the evidence attempt to develop an outline of the late Quaternary climatic history of Western Australia, (2) to formulate the mechanism of one palaeoclimatic event—widespread aridity—which is likely to have been a recurrent feature of the Quaternary climatic history of Western Australia. As far as possible the evidence is reviewed under separate subject headings, but in places material which is not encompassed by a particular section heading is included to avoid clumsy cross-referencing and repetition between sections. Figure 1 shows the location of many of the sites referred to in the text.

Biotic evidence

Evaluating the climatic implications of faunal and floral remains has been one of the mainstays of Quaternary palaeoclimatic reconstruction. In Western Australia few studies of biotic remains have so far been undertaken with the specific aim of reconstructing the Quaternary climatic history of the area. Especially regrettable is the limited use that has been made of palynology, a technique which in other parts of the world has been fundamental in elucidating the Quaternary environmental history.

Biotic distributions

As probable indicators of Quaternary climatic events in Western Australia, disjunct distributions of flora and fauna have attracted a great deal of attention. Considerable discussion has surrounded the apparent west-east and north-south affinities in the distribution patterns of the Australian flora (Gardner 1942; Specht 1958; Burbidge 1952, 1959, 1960; Gentilli 1961; Green 1964; Marchant 1973; Nelson 1974). A comparison of the vascular floras of south-west and south-east Australia by Green (1964) revealed the existence of several hundred species common in both areas but not in the drier intervening regions. Green considered that some of these populations are true vicariads (defined as closely related allopatric species which have descended from a common ancestral population and attained at least spatial separation) which once occupied continuous areas which became broken by the onset of drier climatic conditions. Some examples include *Lepidosperma angustatum* (south-west), *L. concavum* (south-east); *Casuarina decussata* (south-west), *C. torulosa*

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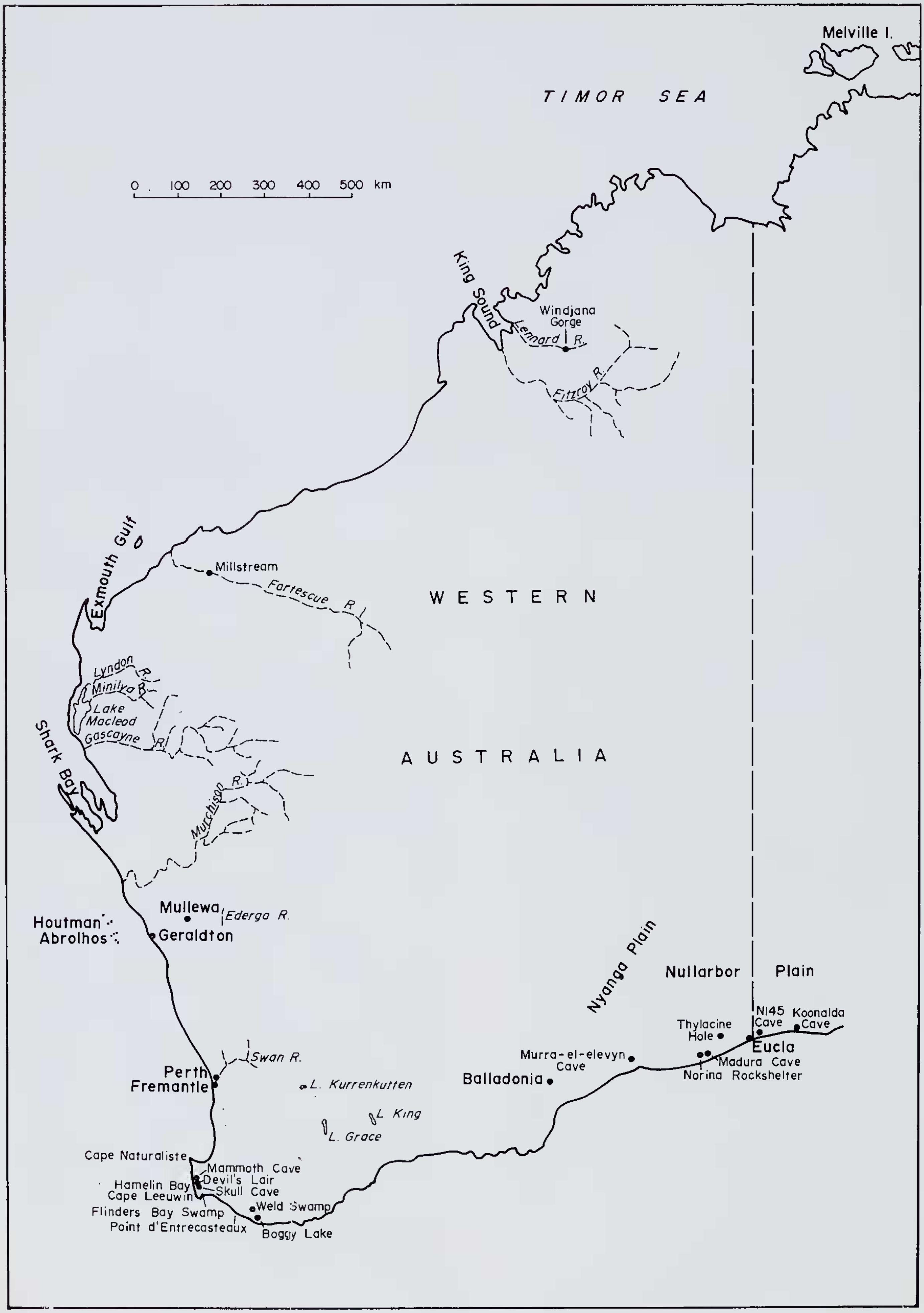

Figure 1.—Location map showing the major sites mentioned in the text.

(south-east); *Acacia leptoneura* (south-west), *A. rigens* (south-east). Estimates as to when this separation of the south-west and south-east flora occurred are widely conflicting, and range from the late Tertiary to the late Quaternary.

North-south affinities in plants are well documented in Western Australia. Gardner (1942) for instance, explained the occurrence in the Geraldton-Perth area of plants common in the Kimberley district, (e.g. *Cartonema, Dioscorea* and *Clematicissus*), as the result of the extension of tropical conditions further south at some time in the past. Other examples include the existence of species of *Terminalia, Owenia, Mallotus* and *Lysiphyllum* in the Pilbara district (Burbidge 1959). The occurrence in tropical areas of isolated species of genera which are well developed in the South-West Botanical Province has been interpreted by several authors as being indicative of the former extension of southern climatic conditions further north (Gardner 1942; Burbidge 1952, 1959, 1960; Gentilli 1961). One species of *Byblis* occurs only in the South-West Province while the only other species in the genus is widespread in the tropical zone. *Verticordia* is mostly confined to the South-West Province and a contiguous semi-arid belt further inland, while in the tropical zone the genus is represented by several species. Other examples include species of *Borya, Persoonia, Boronia, Jacksonia* and *Calytrix* (Burbidge 1960). A relict plant distribution which has not received much attention is the Millstream Palm (*Livistona alfredii*) which is confined to the Fortescue River area at Millstream and a few nearby localities. This species represents the only natural occurrence of palms in Western Australia outside the Kimberley district (Environmental Investigations, Fortescue River 1975).

A number of writers have explained the modern distribution of some amphibians, reptiles, marsupials and birds, east and west of the Nullarbor Plain as the result of greater aridity in the past (e.g. Serventy and Whittell 1976; Main *et al.* 1958; Keast 1961; Kluge 1967). Main *et al.* (1958) explained the existence of frogs with eastern affinities in south-western Australia as the result of successive movements from the primary speciation area in south-eastern Australia across the southern Nullarbor Plain during "pluvial" periods of the Pleistocene. Intervening arid periods were seen as the mechanism of isolation of the eastern and western faunas. Serventy (1951) reached similar conclusions concerning the speciation of the chestnut-shouldered wrens *(Malurus)* which occur throughout the Australian region. Serventy and Whittell (1976) noted numerous examples of the discontinuous occurrence of related avian fauna in Australia. Again the onset of arid conditions during the Pleistocene was invoked to explain these features. Ford (1974), however, has suggested that some isolates of desert species of birds may have formed during relatively wet periods in the Pleistocene.

The only way that the various authors were able to suggest a possible time at which the distributions became separated was by placing them in the context of the palaeoclimatic record available at their time of writing; as the record was often incomplete or in error their conclusions were understandably misleading. This necessity to resort to an existing palaeoclimatic chronology, in order to date a climatic event, postulated on the basis of a disjunct distribution, is a major limitation in the use of disjunct distributions in palaeoclimatic reconstruction. Consequently biotic distributions have been of little value in building up the chronology of Quaternary climatic events in Western Australia, although they have proven useful in indicating likely climatic events that may have taken place.

Nullarbor Plain

Biological evidence for Quaternary climatic changes in the Nullarbor Plain is sparse and often poorly dated. Several workers have suggested that the climate of this region has not changed significantly in the last 20 000 years. Faunal remains found in sediments in Koonalda Cave were dated at approximately 20 000 years BP (Wright 1971, p. 24). Thorne (1971) found no evidence from these faunal remains suggesting an environment different from that of today. Martin (1973) examined pollen from three excavations—N145 Cave near Eucla, Madura Cave and Norina rock shelter. She found that the period 20 000 to about 10 000-8 000 years BP appeared to be more arid than the climate of that area today, with annual rainfall averaging about 180 mm. From about 10 000-8 000 to 5 000-4 000 years BP rainfall apparently increased, and has since maintained an annual average of about 250 mm. The climatic changes indicated by the varying pollen ratios were primarily explained by Martin as being due to the influence of a rising sea level and the consequent climatic effects resulting from a closer proximity to the coast. Martin also suggested that a change in the level of the Aboriginal population at about 4 000-6 000 years BP in the area may have influenced the vegetation patterns.

There is some additional evidence that seems to support Martin's (1973) conclusion that since the middle Holocene the rainfall received by the Nullarbor Plain area has been at the same level as today. The preservation of soft tissue on a *Thylacinus cynocephalus* (Tasmanian tiger) skeleton in Murra-el-elevyn cave (dated at 3 300 years BP, Partridge 1967) and in Thylacine Hole (dated at 4 600 years BP, Lowry and Merrilees 1969) suggested to Lowry and Jennings (1974) that conditions in the caves could not have been much wetter in the intervening time than at present. Ingram (1969) examined the pollen grains found in the desiccated gut of mammalian carcases—*Megaleia rufa* (red kangaroo), *Trichosurus vulpecula* (possum), *Onychogalea lunata* (crescent nail-tail wallaby) and *Canis familiaris dingo* (dingo)—found in Thylacine Hole. These carcases are considered to be between 2 000 and 5 000 years old because they were associated with a *Thylacinus cynocephalus* carcase which has been radiocarbon dated at 4 650 ± 153 years BP, and a *Canis familiaris dingo* carcase which has been dated at 2 200 ± 96 years BP (Lowry and

Merrilees 1969). The fact that the fossil pollen belong to genera common in the present day vegetation, led Ingram (1969) to conclude that the climatic conditions in the area 2 000 to 5 000 years ago, were similar to those of today.

The conclusions of Ingram (1969), Thorne (1971) and Martin (1973) support the view of Jennings (1967), based on the retarded karst development of the Nullarbor Limestone, that there is little evidence for significant climatic changes in the Nullarbor Plain during the Quaternary. In a more recent publication Lowry and Jennings (1974) suggested that there have been changes in the water availability and effective precipitation in the Nullarbor karst during the Quaternary, but that they have never departed substantially in either direction from the present state. They concluded that the karst development on the Nullarbor "may owe much to the cold phases of the Pleistocene when effective precipitation, if not absolute precipitation, was in all probability greater than at present though still low" (Lowry and Jennings 1974, p. 79).

There is some evidence which may support the view of Lowry and Jennings that there was an increase in effective precipitation on the Nullarbor Plain during the Pleistocene glacial periods. Glauert (1912) found the remains of relatively large extinct marsupial species in the Balladonia area, and interpreted them as evidence of a more moist climate at some time during the Pleistocene. Similarly the finding of *Sthenurus* (an extinct large kangaroo) in Madura Cave led Lundelius (1963) to infer more humid conditions in the Pleistocene. These arguments for wetter conditions were based on the assumption that the "giant" marsupials could not have survived in relatively dry habitats. Such an interpretation can be questioned because existing large marsupials in Australia appear to thrive under conditions more harsh than those now prevailing at the fossil sites of the Nullarbor Plain (Lowry and Jennings 1974). However, other evidence which may support Glauert's conclusion, is offered by Richards (1971) who considered that the ancestors of various arthropods found in Nullarbor caves must have colonised that area when conditions were wetter. Furthermore, fossil land snails found in kankar from the Nyanga Plain (the area to the north and west of the Nullarbor Plain) were tentatively compared with the living species *Bothriembryon barretti* by G. Kendrick (in Lowry 1970). While the fossil snails were found within the 150 mm isohyet, Lowry (1970) has found living snails only in areas with more than 250 mm of rainfall. With the absence of absolute dates and reliable stratigraphic information it is not possible to use this evidence to evaluate the suggestion that the climate of the Nullarbor may have been wetter during the glacial periods of the Pleistocene. Nevertheless, the evidence does at least suggest that wetter conditions have occurred.

South-west

Early work on cave deposits in the Cape Leeuwin-Cape Naturaliste region by Glauert (1910, 1914), Lundelius (1960) and others has been revised in a series of papers by Merrilees (1968a, b), Dortch and Merrilees (1972), Baynes *et al.* (1975), Balme *et al.* (1978), Porter (1979) and Merrilees (1979). They report a well-dated continuous sequence beginning before 37 000 years BP (Mammoth Cave), from about 35 000 to 5 000 years BP (Devil's Lair) and from before 8 000 years BP to the present day (Skull Cave), with notes on other less well-dated sites.

It is clear that the region supported a very diverse mammal fauna in the Pleistocene. Some of the species represented in the cave sequences have a wide climatic tolerance (e.g. *Trichosurus vulpecula*—brush-tailed possum); species indicative of drier conditions are also found (e.g. *Bettongia lesueur*—burrowing rat-kangaroo); and remains of species which required rather wet, well-vegetated surroundings are also present in the cave deposits (e.g. *Potorous tridactylus*—long-nosed rat-kangaroo). At some time not yet precisely dated (or perhaps over some considerable period) many large species including *Zygomaturus trilobus* (a diprotodontid) disappeared from the record, and at some time later (late Pleistocene to early Holocene) several of the species most characteristic of drier climates, including *Macroderma gigas* (ghost bat), retracted their ranges out of the region.

The reasons for the disappearance of the large extinct species are still obscure, but Merrilees (1979) suggests that the "dry climate" species were displaced in early Holocene time by the development or extension of dense karri forest like that of early historic time. The implication is that higher effective rainfall, perhaps with less extreme difference between wet and dry seasons, marked the beginning of the Holocene.

An indication of possible Holocene climatic variations in the extreme south-west is given by Churchill (1968), who suggested that rainfall is the major determinant of the distribution of *Eucalyptus marginata, E. diversicolor* and *E. calophylla*. Changes in the *E. diversicolor/E. calophylla* ratio were thought to provide an index of precipitation changes; a relative increase of the *E. diversicolor/E. calophylla* ratio being indicative of wetter conditions. It appears from pollen analyses at Flinders Bay Swamp, Weld Swamp and Boggy Lake that conditions were relatively wetter between 6 000 and 5 000 years BP, followed by a trend towards drier conditions until about 2 500 years BP; after which wetter conditions apparently prevailed until about 1 300 years BP, subsequently it became drier until about 500 years BP. From then to the present there was a trend towards higher rainfall. The similarity of Churchill's findings, that in the south-west conditions were wetter between 6 000 and 5 000 years BP, with the changes recorded in lakes of western Victoria (Dodson 1974a, b) and on Wilson's Promontory, eastern Victoria (Hope 1974) led Bowler *et al.* (1976) to suggest that this constituted a climatic event which affected much of southern Australia. Kendrick (1978) described an assemblage of land snails from palaeosols occurring on and beneath the surface of an elevated ridge of aeolian calcarenite from near Point d'Entrecasteaux. He concluded that the assemblage—*Bothriembryon* *gardneri*, *B. consors*, species of *Paralaoma*, *Magilaoma*, *Pernagera*, one other charopid and an undescribed assimineid—suggests a humid, well vegetated, probably forested environment in the Point d'Entrecasteaux area at the time of soil formation, in contrast to the exposed coastal heath that presently characterises the area. Unfortunately the actual age of this assemblage is as yet unknown.

Kendrick (1977) found that fossil molluscs from a mid-Holocene deposit near Guildford have a greater marine affinity than the present assemblage in that area. The fossil deposits have a radiocarbon age of 6 600 ± 120 years BP, coinciding approximately with the Holocene marine transgression. It follows that a greater marine influence would be expected in this part of the Swan River at that time. But despite this, given the present river discharge conditions near Guildford, Kendrick argued that river discharge and seasonality were much lower than at present, which implies that drier climatic conditions prevailed in the Guildford region from at least 6 700 years BP until some time after 4 500 years BP.

Northern areas

Kendrick (1978) has recently described two new species of *Bothriembryon* snails from palaeosols in the Shark Bay district. The two species, *B. douglasi* and *B. ridei*, have no known living descendant in that area. Their extinction at about 80 000 years BP, and the subsequent appearance of camaenid snails (*Rhagada*, *Plectorhagada* and *Angasella* species), as well as the size reduction of *B. costulatus*, are thought to have resulted from the onset of more arid conditions in that area at that time. More humid conditions are thought to have returned to the area since about 10 000 years BP.

Other evidence of Pleistocene climatic events in northern Western Australia comes from Mayr (1944) who discussed the avian faunal exchanges which evidently occurred between Timor and Australia during the period of each Pleistocene glaciation. The fact that most of the recent arrivals from Timor were grassland birds led Mayr to conclude that the climatic conditions prevailing during each glacial were at least as dry or drier than at present. A vertebra from the Ederga River and a tooth from the Gascoyne River district mentioned by Merrilees (1968b, p. 15, the latter tentatively classed as "varanid") may represent crocodilians (D. Merrilees, 1978, pers. comm.), and if so, would imply a possible southward extension of tropical conditions at some time in the Pleistocene.

Gorter and Nicoll (1978) have recently discussed the occurrence, at Windjana Gorge, of indeterminate crocodilian and turtle remains in river gravels of possible Pleistocene age, which may however be as old as early Miocene. The authors claim that the crocodilian remains do not have any important palaeoenvironmental significance. But the presence of remains of the river turtle *Carettochelys* implies a warmer climate than the present one in north-western Australia. However, Gorter and Nicoll stress that without more evidence this conclusion is speculative.

An indication of part of the Holocene climatic history of the northern areas is given by Jennings' (1975) work in the Fitzroy estuary. At present this area experiences a long dry season which in part results in low mangrove forest and mangrove scrub. The stratigraphy of two embayments in the Fitzroy estuary indicates a much wider extent of mangrove swamp at about 7 400-6 000 years BP. In addition the occurrence of fossil stumps of mangrove larger than those of today suggest that tall mangrove forest prevailed at that time. From this, Jennings concluded that at the time a longer and heavier wet season characterised the Fitzroy region. In support of his conclusions Jennings cited Stocker (1971) who suggested that a decline in annual rainfall or a lengthening of the dry season had taken place on Melville Island between 8 000 and 2 000 years BP. Present day jungle fowl on Melville Island inhabit closed communities, particularly monsoon forest. The discovery of ancient mound nests in eucalypt forest led Stocker (1971) to suggest that there has been a gradual decrease in monsoon forest on the island resulting from either a reduction in rainfall or the effects of the Aborigines through their use of fire.

Geomorphological-geological evidence

Longitudinal sand dunes occupy a large area of the Australian continent, but are presently active only in the arid centre. The occurrence of vegetated dunes on the present desert margins, similar in form to their more arid counterparts, provide the most striking evidence of the extension of more arid conditions, at some time in the past. An understanding of the timing and development of these sand dunes, taken in conjunction with the evidence from lake lunettes, has added much to our understanding of Australian Quaternary palaeoclimates (see Bowler (1976) for a review of much of this evidence).

In Western Australia aeolian evidence for a former extension of arid conditions is widespread. Veevers and Wells (1961) described the now stabilised sand dunes and sheets of the Canning Basin, and attributed their development to an arid phase some time in the Pleistocene. Earlier work by Fairbridge (1953) and Brunnschweiler (1957) had already led to the recognition of now stable large aeolian bedforms in this area. Both authors attributed them to the occurrence of extended arid conditions during the Pleistocene. Brunnschweiler (1957) suggested that the inland dunes of the Dampier Peninsula (a term he applied to the area west of King Sound) are continuous with dunes further inland, and proposed that the dunes formed in the Pleistocene during a period corresponding with the Riss Glacial of Europe; however there is no evidence put forward by the author which supports this age estimate. Fairbridge (1953) followed Mayr's (1944) discussion, referred to in an earlier section, and concluded that these dunes stem from a glacial period. In a later work

Fairbridge (1964) compared the way the fixed longitudinal dunes in the Fitzroy area appear to descend below present sea level, as also described by Wright (1964), with an analogous situation in the lower Senegal Valley, and postulated arid conditions and associated dune formation in the Fitzroy area during the last glacial.

The stratigraphic evidence provided by Jennings (1975) confirmed the superficial appearance of the burial of the desert dunes by estuarine fill. A minimum age of 8 000 years BP was inferred from the depth of buried dune sand, while a maximum age of about 140 000 years BP was suggested on the basis of well-presented dune shape. Jennings (1975) related his findings to those of van Andel *et al.* (1967) who interpreted the occurrence of brown calcareous nodules (kankar) in the sediments dated at 17 000 years BP on the Sahul Shelf, as evidence of drier climatic conditions at the last glacial maximum. From this evidence Jennings (1975) reached the conclusion that the most probable time for dune formation in the Fitzroy area was at approximately 20 000 years BP.

Evidence in support of this age estimate for the formation of these dunes comes from the abundance of quartz in Indian Ocean sediments dated at about 18 000 years BP (Kolla and Biscaye 1977). The quartz particles found in these sediments are derived from the adjacent continental area, and the higher amounts of quartz in the sediments suggest increased continental aridity and/or increased intensity of wind at the time of deposition.

Further south in the Exmouth Gulf area at least two inland dune units can be distinguished (Wyrwoll, unpublished). Both appear to predate the Holocene transgression. The older dune unit is capped by a thick indurated calcrete horizon, while on the younger dunes more weakly developed calcareous soils are found. No absolute ages for these dune units are yet available. The presently vegetated dunes of the Gascoyne-Minilya-Lyndon Plain appear to correspond to the younger dunes of the Exmouth Gulf. This dune unit seems to predate the evaporite sequence of Lake Macleod. So far it has not been possible to develop a convincing stratigraphy of the Quaternary sediments of the Exmouth Gulf-Gascoyne area which would time bracket the two dune units with sufficient resolution.

Logan *et al.* (1970) describe two red sand dune units in the Shark Bay region. In the upper part, the older unit (the Peron Sandstone) has a strongly developed nodular calcrete horizon. The Peron Sandstone may correspond to the older dune unit recognised in the Exmouth Gulf area. Although Logan *et al.* provide a comprehensive account of the stratigraphy of the Quaternary sequence of the Shark Bay area, the absolute age of the Peron Sandstone remains uncertain. However, the Peron Sandstone is overlain by the Dampier Transgression, and $^{230}Th/^{234}U$ dating on corals from this transgression is now being undertaken (W. J. E. van de Graaff, 1978, pers. comm.), which will provide at least a minimum age for the Peron Sandstone. The younger dune unit, the Nilemah Sands of Logan *et al.*, consists of unconsolidated red sands which overlie the other Pleistocene formations of this area. This unit corresponds to the unconsolidated dunes of the Gascoyne Plain-Exmouth Gulf region. Degraded inland dune forms can be identified as far south as the Geraldton-Mullewa area (Johnson *et al.* 1954; Wyrwoll unpublished). Further inland Mabbutt (1963a, b) found that an arid event affected the Murchisonia and Salinaland divisions (Jutson 1950), but was unable to determine an age for this event, except to conclude that it took place some time during the Pleistocene. The yellow sands which occur throughout the Perth Basin have been interpreted by Glassford and Killigrew (1976) as a relict aeolian desert sediment derived from sources on the Yilgarn Block and in the Perth Basin. Their conclusion is based on the textural characteristics and mineralogy of the sands, and the occurrence in the sands of kaolin spherites (see Killigrew and Glassford 1976) which they claim have not been observed in marine derived coastal dune or aeolian calcarenite sediments.

In the south Bowler (1976) has dated lunette deposits which fringe Lake Kurrenkutten, Storey's Lake, Lake Grace and Lake King. The results indicate that a short-lived lunette-building event took place between 20 000 and 15 000 years BP, during a period of hydrologic stress; this is an event which has been widely recognised throughout much of southern Australia.

Other geomorphological evidence of Quaternary climatic change in Western Australia is not well documented. The conclusions that Jennings (1967) and Lowry and Jennings (1974) arrived at with respect to the degree of karst development on the Nullarbor Plain have already been noted. Wright (1964) envisaged that the onset of drier climatic conditions in the Pleistocene led to the formation of floodplains along the Fitzroy and Lennard Rivers and their tributaries; and to the extensive alluviation marginal to upland areas in the Fitzroy Basin. Further south in the Geraldton area a "Red Alluvium" unit has been described, and dated at earlier than approximately 40 000 years BP (Wyrwoll 1977). The "Red Alluvium" overlies marine deposits, which on the basis of the molluscan fauna and coastal stratigraphy, were attributed to a last interglacial high sea level, thought to have occurred at about 120 000 years BP (Veeh 1966). At the time of deposition of the "Red Alluvium" streams carried a much coarser bed load than at present, and appear to have had a greater competence and capacity than the present streams. Sediment yields at the time of deposition of the "Red Alluvium" were almost certainly considerably higher than at present. It was tentatively concluded that semi-arid conditions with intense rainfall events occurring more frequently than today, may have prevailed at the time of deposition of the "Red Alluvium".

A fine textured, inset alluvial fill from the Geraldton area, described informally as the "Grey Alluvium" and originally dated at 3 185

± 145 years BP (Wyrwoll 1977) has recently been used by Williams (1978) to support a postulated continent-wide climatic change between approximately 4 000 and 1 500 years BP. In the Southern Tablelands of New South Wales this event may have led to a change in rainfall seasonality, to lower temperatures, and to drier, windier conditions. Since the original date was published an additional ^{14}C date with an age of 1 375 ± 120 years BP (GX-5133), has been obtained for the "Grey Alluvium". The two dates demonstrate the diachronous nature of this alluvial deposit, and question the validity of using the older date as a reliable upper limit for the age of the "Grey Alluvium".

A discussion of the palaeoclimatic significance of palaeosols found in the Tamala Limestone was undertaken by Fairbridge and Teichert (1952). These authors believed that the soil horizons which separate a number of dune generations in the Tamala Limestone indicate minor and short-lived climatic cycles. They claim a change from rendzinas near Hamelin Bay, to terra rossas at the latitude of Fremantle, and travertine crusts along the coast, further north of Houtman Abrolhos. The authors suggest that this gradation of fossil soils confirms their belief that at times during the Pleistocene most of the south-west was subject to more arid conditions.

Limitations of the evidence

Several authors have pointed out the limitations of the various lines of evidence that have been used for Quaternary palaeoclimatic reconstruction in Australia (Jones 1968; Merrilees 1968b; Ride 1968; Calaby 1971; Galloway 1971; Walker 1976, 1978). It has become apparent that palaeoclimatic inferences drawn from plant and animal remains should be made with caution. Walker (1976) has painted a rather grim picture of the present reliability of pollen data for postulating past climatic conditions. In the context of faunal remains and distributions Calaby (1971) has pointed out that homoiothermic and at least the larger poikilothermic animals, have a wide climatic tolerance. The possible role that the Aborigines played in modifying the ecology of the Australian biota (Tindale 1957; Merrilees 1968b; Jones 1968, 1975; Hallam 1975) must also be considered when interpreting biotic evidence in terms of palaeoclimatic events.

Similarly the geomorphological-geological evidence poses considerable problems. The use of alluvial deposits as palaeoclimatic indicators has led to imprecise and often widely conflicting results (see the summary in Flint 1971, p. 306). The reasons why such discouraging results have been obtained can be readily understood when the factors controlling the likely alluvial response to climatic changes are considered, and the equifinality of the problem appreciated (e.g. Schumm 1965; Gessler 1971). Approaching the study of alluvial deposits from the point of view of the palaeohydraulics of the sediments may overcome at least some of the difficulties.

The absence of reliable dates for dune-building phases is also a major stumbling block, although it is hoped that dates from pedogenic carbonate may at least give some indication of the timing of these events. The interpretation of the Perth Basin yellow sand as a relict aeolian desert sediment has been criticised by Lowry (1977), and although some of the criticism has been answered by Glassford and Killigrew (1977), the need for a more comprehensive presentation and discussion of the evidence remains (cf. Clark and Dortch 1977, who also consider the age and origin of the yellow sand).

Chronology of events

The weakness of the available evidence is highlighted when any attempt is made to outline the chronology of the late Quaternary climatic history of Western Australia. The absence of a continuous record, the few absolute dates, and the problems associated with the interpretation of the available evidence, make it impossible to give anything other than a crude and incomplete outline of the late Quaternary climatic history of this area.

80 000-20 000 years BP. Evidence from the central coastal area suggests that in this area the beginning of this period may have seen the onset of arid conditions, which appear to have prevailed until the beginning of the Holocene. The early part of this period saw the frequent occurrence of high precipitation events leading to high sediment yields, and resulting in extensive aggradation in the Geraldton area. The now drier parts of the south may have experienced an increase in effective precipitation during part of this period.

20 000-10 000 years BP. Until about 14 000 years BP intense widespread aridity affected much of Western Australia. The now stabilised and partly degraded dune fields, which in the coastal region extend from the Fitzroy to the Geraldton-Mullewa areas, were formed during this period. The Devil's Lair sequence suggests a significant reduction in the effective precipitation of the lower south-west at the same time. In the south-west and Nullarbor Plain relatively dry conditions seem to have prevailed until the end of the Pleistocene.

10 000 years BP to present. The climatic record for this period as for the earliest period is very incomplete. The onset of the Holocene, with a rising sea level and higher sea surface temperature is likely to have seen a significant increase in precipitation over much of Western Australia. During the period 7 400-6 000 years BP, the north-west appears to have received a higher rainfall which extended further south than at present. More arid conditions may have prevailed in the south-west from 6 700 years BP to about 4 500 years BP. The pollen evidence from the extreme south-west suggests increased precipitation over the period 6 000-5 000 years BP, followed by drier conditions which prevailed until 2 500 years BP.

Mechanism of arid-zone extension

A dominant theme which emerges from the available literature is the apparent expansion of the arid zone, probably at various times during the Quaternary. The most recent widespread expansion appears to be well documented and seems to have coincided with the last glacial maximum (Jennings 1975; Bowler 1976; Wyrwoll and Milton 1976; Kolla and Biscaye 1977). This was an event which in Australia led to an extension of the arid zone along the whole of its present perimeter (Bowler *et al.* 1976); and which can be related to the expansion, at that time, of low latitude arid areas throughout the world (Sarnthein 1978).

Few attempts have been made to interpret this generally accepted expansion of the arid zone in terms of the climatic controls that may have prevailed at that time. One approach that can be taken to obtain an indication of the dynamic palaeoclimatology of past events, is to use the extremes of the present circulation as an analogue for past conditions (see Barry 1975). The assumption inherent in any analogue approach is that the present-day climatic variability includes conditions which were sufficiently frequent in the past to give rise to a substantially different climatic regime (Dzerdzeevski 1963). This amounts to assuming a form of climatic uniformitarianism which, in the light of changing boundary conditions and a possibly almost "intransitive atmosphere"—where the set of equations which represent the behaviour of the atmosphere has a number of solutions, each representing a possible condition of the atmosphere (Lorenz 1976)—is unrealistic. Even over decades, changes of climatic characteristics have been recognised that cannot be attributed to changes in the frequency of a particular circulation pattern, but which arise through changes in the characteristics associated with the circulation (e.g. Perry and Barry 1973). Despite these serious limitations an analogue approach may serve as a useful first approximation to a partial explanation of past climatic events.

The present climate of Western Australia is strongly influenced by the subsiding air of the sub-tropical high pressure belt (STH) (Gentilli 1971, p. 53) which is linked with the descending branch of the low-latitude Hadley cell—the direct cause of much of the widespread aridity of sub-tropical latitudes (Hare 1961). The seasonal displacement of this belt is an important control on both the summer precipitation of the north and the winter rainfall of the southern areas of Western Australia.

The seasonal shifts of the Intertropical Convergence Zone (ITCZ) dominate the dynamic climatology of the northern areas. It is in this zone that the tropical rain-producing disturbances originate (Charney 1968; Bates 1970), so that the location of this feature is fundamental in determining the rainfall of adjacent areas. The location of the ITCZ is linked to the meridional temperature gradient of both hemispheres (Newell 1973), and seems to be determined by low-level convergence in the tropical boundary layer (Charney 1968). Prevailing sea-surface temperatures also seem to play an important role in determining the location of the ITCZ (Charney 1968; Pike 1971). The ITCZ only reaches northern Australia in summer when the STH has been displaced to the south. Associated with the ITCZ is an inflow of moist, unstable air which gives rise to the "Australian summer monsoon". This monsoon circulation however, is shallow and weak, and only a pale imitation of its Asian counterpart.

Despite the fact that during the summer months the STH cells are located far to the south, they can still exert a marked influence on the precipitation of the northern areas. Intense anticyclones situated over the Australian Bight can give rise to a quite stable atmosphere above the Pilbara heat low, and through this prevent the incursion of monsoonal depressions and disturbances into the northern areas (Rutherford and Hannan 1956; Falls 1970).

A comparison between the rainfall received by northern Australia in February 1952, and February 1953, highlights the control that the STH exerts on the rainfall of the northern areas. In February 1952, when northern Australia was in the middle of its worst drought in 60 years, the highs migrated 5° closer to the equator than normal. In February 1953, however, when rainfall was high the track of the migrating highs lay up to 10° poleward of normal (Ramage 1971, p. 273).

The winter rainfall of the southern area of Western Australia is largely associated with moist unstable westerly winds and with the associated troughs in this westerly airstream. The mean depression track and the associated zone of maximum rainfall are situated off the south-west coast, and this accounts for the decreasing precipitation gradient northward (Wright 1974). Pittock (1973, 1975) has demonstrated a correlation between the latitude of the STH and the amount of precipitation received by the south-west. This correlation has been substantiated by Wright (1974) whose work focuses on the south-west of Western Australia. These authors have shown that a more southerly location of the STH can significantly reduce the winter rainfall received by the south-west.

Using the present climatic regime as an analogue for past conditions it is evident that an increase in anticyclonicity would directly result in widespread aridity over much of Western Australia. Wyrwoll and Milton (1976) have argued that the lowering of the mean July sea and land surface temperatures (Climap 1976; Gates 1976a, b) would have thermally intensified the anticyclone. The resultant anticyclone would have combined the high pressure qualities of both anticyclonic types—warm and cold (Wexler 1951)—and therefore would have been extremely intense (also see Derbyshire 1971). Under these conditions the frequency of breakdown of anticyclonic cells would have been considerably lower, and with the consequent development of blocking conditions, winter rainfall would have been confined to the extreme south-west of Western Australia.

To describe the synoptic conditions governing the summer months during full glacial periods it was envisaged (Wyrwoll and Milton 1976) that anticyclonic conditions would have weakened, but possibly only to the extent that conditions were more similar to those of the present day late spring or early autumn. This would imply that during the full glacial summer the STH was located significantly further north than during the present summer months. From the present day situation it is clear that this would have been a very effective mechanism in reducing the rainfall received by the northern areas.

A northward displacement of the STH during glacial summers is supported by the so called "Z" criterion developed by Smagorinsky (1963), and subsequently used by Flohn (1964, 1965) for locating the position of the STH. The "Z" criterion takes the form

$$\cot \phi = - \frac{a}{h} \frac{\partial \ln \theta_{PE}/\partial y}{\partial \ln \theta_{PE}/\partial z} \qquad (1)$$

where ϕ is the latitude of the STH, h a scale height of the atmosphere of about 9 km, which approximates the height of the 500 mb surface, and a is the radius of the earth, θ_{PE} is the partial potential equivalent temperature (see Appendix 1), and z and y are the vertical and horizontal axes respectively. Instead of using the potential equivalent temperature Flohn (1965) has approximated equation (1) by using the potential temperature (θ) and by relating this to the actual temperature, Flohn has prepared a nomogram from which the effect of changes in the meridional and vertical temperature gradients on the position of the STH can be read (Fig. 2).

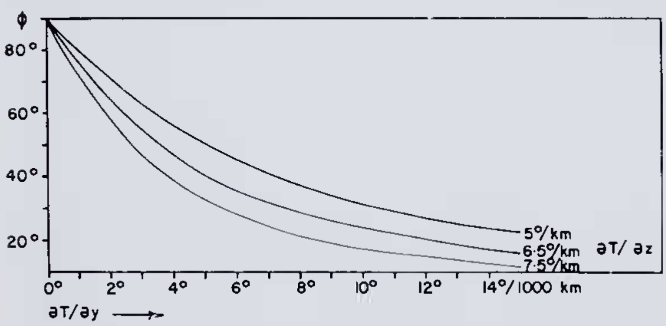

Figure 2.—Location of the subtropical high pressure cell (ϕ) as a function of the meridional and vertical temperature gradients (after Flohn 1965).

The validity of the "Z" criterion appears to have been established by Korff and Flohn (1969) who demonstrated a close relationship between the monthly mean equator-pole potential temperature gradient—which they took as a crude approximation for $\partial \theta_{PE}/\partial y$—and the position of the STH. Further support was offered by Pittock (1973), who found that equation (1) fairly accurately predicts the monthly mean latitude of the STH over Australia. However, Greenhut (1977) has recently developed a new criterion for locating the STH which predicts an opposite response to changes in $\partial \theta_{PE}/\partial y$ and $\partial \theta_{PE}/\partial z$ to those predicted by the "Z" criterion. It is difficult to reconcile the prediction of this new criterion with the success met by Korff and Flohn and Pittock when using the "Z" criterion. These two studies would appear to suggest that the adoption of the "Z" criterion is a valid first approximation despite Greenhut's conclusions.

During glacial periods the overall meridional temperature gradient of the upper troposphere may have been similar or even less than that of today (Kraus 1973; Williams 1978). However, it is likely that a strengthened meridional temperature gradient occurred in the middle troposphere over the mid-latitudes. According to Korff and Flohn these are the latitudes which determine the location of the STH. From Figure 2 it is evident that an increase in the mid-latitude meridional temperature gradient would be further enhanced if an increase in the vertical temperature gradient had taken place. For equatorial areas Kraus (1973) suggested that during glacial conditions a three-fold amplification of the changes in sea surface temperature occurred by the time the ascending air reached the upper troposphere. This occurred as the result of a decrease in latent heat release, and would only be significant over areas with a sea surface temperature greater than approximately 20°C. In addition there is some evidence from South-East Asia (Verstappen 1975) and New Mexico (Wright *et al.* 1973) that during full glacial conditions a lapse rate of temperature with height greater than present, may have prevailed at least in the lower latitudes. The combined evidence suggests that an equatorward displacement of the STH during full glacial conditions would have been highly likely.

A northward displacement of the STH should result in a concomitant displacement of the ITCZ and the depressions associated with it. Available evidence (Bryson 1974; Beer *et al.* 1977) suggests that the amount of northward displacement of the STH would be amplified, possibly up to three times, with respect to the ITCZ. Evidently an equatorward displacement of the STH would be very effective in causing the extension of arid conditions in the northern areas.

In addition, because of the high contribution that tropical cyclones make to the annual precipitation of the north-west (Milton 1978), widespread aridity in that area during the last glacial maximum implies an absence of tropical cyclones at that time. Whether this was due to an absence of cyclogenesis as a result of reduced sea surface temperatures (Webster and Streten 1972) or simply a more westerly seaward path is not possible to establish. As tropical cyclones are very effective converters of potential to kinetic energy, and play an important role in the general circulation of the atmosphere (Landsberg 1960), a possible absence of tropical cyclones during full glacial periods would have important repercussions on the general circulation.

An equatorward displacement of the STH during full glacial stages has also recently been suggested by Rognon and Williams (1977) and appears to be supported by the available geomorphological evidence. The orientation of clay lunettes in southern Australia suggests that the summer anticyclone over Australia in full glacial times was positioned some 5° further north than today (Bowler 1976). In addition Bowler envisaged a strengthening of the westerly air flow over southern Australia at that time. In Western Australia the geomorphological evidence of dune and lunette orientation appears to support this reconstruction. But this circulation pattern is fundamentally different from that required by Glassford and Killigrew (1976) to account for the derivation of the Perth Basin yellow sand. Their interpretation implies that surface easterlies prevailing as far south as the Leeuwin Block, occurred with sufficient frequency and intensity to transport large volumes of sand westward. This, taken in conjunction with the proposed extension of desert conditions to the coast, could only occur under a circulation pattern in which the STH during a large part of the winter, is located further south than its present summer location. From equation (1) it follows that this could only occur during periods in which a substantial increase in $\partial\theta_{PE}/\partial z$ and/or a decrease in $\partial\theta_{PE}/\partial y$ had taken place. While it would seem that such an extreme southward displacement of the winter STH is unlikely, if it did occur it would almost certainly have occurred during interglacial stages.

During the present interglacial the maximum southward displacement of the STH should have occurred at the "climatic optimum" (approximately 6 000 years BP) when increased global temperatures and higher atmospheric moisture content may have significantly reduced $\partial\theta_{PE}/\partial y$ and/or increased $\partial\theta_{PE}/\partial z$. From the previous discussion of the present precipitation controls, it follows that if the STH was displaced southward at approximately 6 000 years BP, climatic conditions more arid than at present should have occurred in the south-west of Western Australia at that time. Kendrick's (1977) conclusions seem to support this idea, but this is rather scant evidence in view of the earlier work by Churchill (1968), and the discussion of the Australian mid-Holocene climatic evidence by Bowler *et al.* (1976). However, if it is valid that the location of the STH is as important a control of rainfall in Western Australia as has been suggested, then there is an additional way in which the idea that there was a significant southward displacement of the STH at about 6 000 years BP can be tested, and Kendrick's conclusions at least partially checked. It follows that if a significant southward displacement of the STH took place at that time, and that this displacement also characterised the circulation of the summer months, higher summer rainfall extending further south can be expected in the northern areas at that time. Jennings' (1975) conclusion, that during the period 7 400-6 000 years BP a heavier wet season characterised the Fitzroy region, may lend some support for the idea outlined above.

If it is tentatively concluded that during interglacial stages, a significant southward displacement of the STH can occur, which may lead to more arid conditions in some parts of the south-west, it remains to be shown whether during previous interglacial stages, this southward displacement could have been extreme enough to lead to an extension of arid conditions as far south as the Leeuwin Block. The suggestion that such a massive southward extension of arid conditions may have occurred during a past interglacial stage is certainly difficult to reconcile with what is thought to happen in low-latitude arid areas during interglacial stages (see Sarnthein 1978). In addition aridity extending as far as the coast in a western littoral during a period in which sea surface temperatures were higher than at present is difficult to visualise.

Doubts remain whether it is really necessary to invoke a significant displacement of the STH to account for the aridity of the northern areas during full glacial conditions. Manabe and Hahn (1977) showed that tropical continental aridity at glacial maximum is closely related to stronger surface outflow (or weaker inflow) over tropical areas. This resulted from the hydrostatic response to the greater reduction of surface temperatures over continents than oceans and the increased albedo value that characterised tropical areas at that time. Increased albedo values over sub-tropical areas are important in leading to the extension of arid conditions. Increasing the albedo of a surface contributes to a net loss of radiative heat thereby creating a horizontal atmospheric temperature gradient with respect to the surrounding areas. Through this a circulation is set up which transfers heat aloft and maintains thermal equilibrium through sinking and adiabatic compression (Charney 1975). In sub-tropical areas this subsidence is superimposed on the descending branch of the Hadley Cell, clearly accentuating its effect. The positive feedback relationship which is set up as the result of increased albedo values almost implies that "the desert feeds upon itself" (Charney 1975).

A number of other considerations also point to the fact that during full glacial conditions much of Western Australia must have been much drier than today. Analyses of Indian Ocean cores (Vella *et al.* 1975; Williams and Johnson 1975; Bé and Duplessy 1976) show that during the last full glacial an equatorward shift of the Australian-Subantarctic front and the Sub-Tropical Convergence zone took place, with the result that much lower sea surface temperatures characterised the ocean off Western Australia. Microfaunal and oxygen isotope analysis of core RC9-150 (Bé and Duplessy 1976), taken from the continental slope 125 km north-west of Perth, showed that mean summer sea surface temperatures at 18 000 year BP were up to 6C° lower than those of today.

Sea surface temperatures exert an important control on precipitation (e.g. Namias 1975; Wright 1977), and in tropical areas show a strong correlation with storm frequencies (Wendland 1977). Today the presence of warm water off the coast in winter makes south-western Australia far wetter than any corresponding western littoral (Gentilli 1952, 1971; Lydolph 1957). An examination of the rainfall distribution of the dry western littorals of the various continents (Lydolph 1957), revealed that except for Western Australia the annual rainfall increases inland from the driest area which lies in a narrow coastal strip. This extreme aridity in the immediate coastal belt may be explained by the stabilising effect of a cold offshore current, which today is largely absent off the coast of Western Australia (Wooster and Reid 1963). In the Indian Ocean the low-latitude ocean circulation is strongly determined by the trade winds (Knauss 1963). With an increase in the strength of the trades during full glacial periods, which now seems likely in the light of evidence from different parts of the world (e.g. Parkin 1974; Molina-Cruz 1977) a cold offshore current along the coast of Western Australia can be expected. In any event with the considerably lower sea surface temperatures, that the deep-sea core evidence suggests, a tendency towards aridity should have been pronounced. This conclusion was in part anticipated by Brooks (in Mayr 1944) over 30 years ago. He suggested that during full glacial conditions a cold current was present off the west coast of Australia, which he suggested would only be a winter-time phenomenon. The presence of this current "would have had the effect of extending the winter-time high pressure area and contributing at this season to the aridity of the west coast of Australia" (Mayr 1944, p. 129).

The existence of arid conditions over parts of Western Australia during full glacial periods would have been further facilitated by the exposed continental shelves of those periods. That the increased continentality would result in an appreciable reduction in the precipitation received by the north-west was again pointed out by Brooks, and more recently reiterated by Nix and Kalma (1972). The important control that this mechanism is likely to have had on the late Quaternary climates of the Nullarbor Plain (Martin 1973; Martin and Peterson 1978) was noted in an earlier section.

Summary

Despite the sketchy nature of the evidence it is now apparent that Western Australia experienced widespread climatic changes over the last 80 000 years. Of these changes the most severe was clearly the arid phase which characterised part of the closing 10 000 years of the Pleistocene. Arid-zone extension, coinciding with the global glacial maxima, must have been a recurrent feature of the Pleistocene climatic history of Western Australia. This inference is in part supported by the stratigraphy of the Quaternary sediments of the Shark Bay-Exmouth Gulf area. But it needs to be borne in mind that aridity in Australia finds its origin in the late Tertiary (see Bowler 1976), so that the Pleistocene extensions of the arid zone are the culmination of a trend which started some 10 million years ago. The extreme arid phases of the Pleistocene must have deeply influenced the lives of the original human inhabitants of this part of the continent, and their effect on both flora and fauna was equally profound. Similarly much of the physical landscape still bears the imprint of these phases.

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Appendix 1

The partial equivalent potential temperature is given by

$$\theta_{PE} = K\theta \qquad [A1]$$

where θ is the potential temperature. If air at pressure p and temperature T is brought adiabatically to a standard pressure P_0 of 1 000 mb., its temperature θ at that standard pressure is known as its potential temperature. This is given by

$$\theta = T(P_0/P)^{\kappa} \qquad [A2]$$

$\kappa = (c_p - c_v)/c_p = 0.288$ for dry air

c_p is the specific heat at constant pressure

c_v is the specific heat at constant volume

In equation [A1] the function K introduces the modification in the potential temperature due to the presence of moisture in the air; for details of this see Greenhut (1977).